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Palladium-Catalyzed Suzuki-Miyaura Cross-Couplings with 2-Diethylphosphonato-Substituted Aryl- and Naphthylboronate Esters as the Nucleophilic Partner: A Complementary Approach to the Synthesis of Biaryl Monophosphonates

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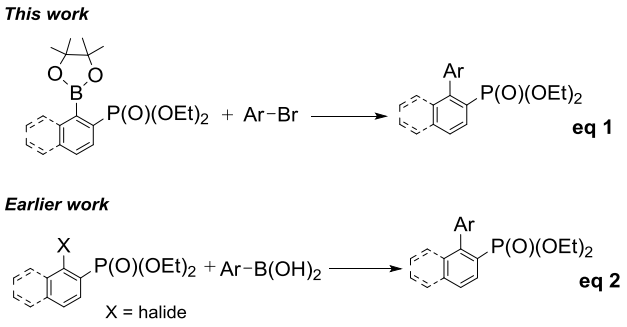
Supporting Information Placeholder

ABSTRACT: This paper reports the first examples of Suzuki-Miyaura cross-couplings involving aryl- and naphthylphosphonate-based boronate esters as the nucleophilic partner. A systematic comparison of the performance of biaryl-like KITPHOS and XPHOS-based systems revealed that between them an electronically and sterically diverse range of substrates can be coupled with remarkable efficiency to afford high yields of the corresponding biaryl and heterobiaryl monophosphonates. The use of an aryl- and naphthylphosphonate-based boronate ester as the coupling partner presents an alternative and potentially complementary pathway to existing couplings in which the aryl- or naphthylphosphonate unit is typically introduced as the electrophile. The potential advantages associated with the use of this new class of coupling partner was clearly demonstrated by the palladium-catalyzed reaction between diethyl [2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl]phosphonate and 1-bromo-2-methoxynaphthalene which gave the corresponding biaryl monophosphonate in 56% yield, a marked improvement on the 6% yield obtained from the reaction between 2-methoxy-1-naphthylboronic acid and diethyl (2-bromophenyl)phosphonate with the same catalyst under the same conditions. The potential utility of this new coupling combination was demonstrated by reducing one of the products, 2-methoxy-1-(2′-diethoxyphosphorylphenyl)naphthylene, to the corresponding primary phosphine, which was subsequently converted into a diastereoisomeric mixture of the *R*,*R*-hexane-2,5-diol-derived phospholane in reasonable yield.

INTRODUCTION

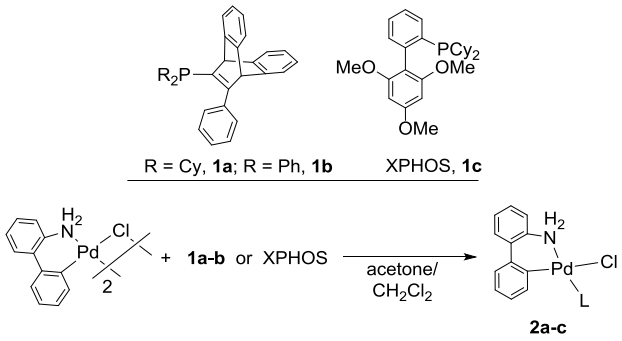
Recent years have witnessed an escalating interest in the synthesis and elaboration of functional biaryl monophosphonates as this motif appears in a host of important bioactive compounds and P-based ligands.[1] Indeed, since their introduction, biaryl monophosphines have evolved into a highly versatile and powerful class of ligand for a host of transition metal-catalyzed transformations.[2-10] While these ligands have been prepared by modifying an existing biaryl unit,[11] Buchwald's one-pot protocol, based on addition of an aryl Grignard to an in situ generated benzyne followed by trapping of the resulting intermediate with a chlorophosphine, is arguably the method of choice as it combines elegance and efficiency with modularity and versatility.[12] More recently, the biaryl framework of monophosphines have been constructed via cycloaddition reactions involving 1-alkynylphosphine oxides and sulphides including microwave-based Diels-Alder cycloaddition-extrusion between a 1-alkynylphosphine oxide and a diene,[13] rhodium-catalysed [2+2+2] cycloaddition of a tethered diyne with a 1-alkynylphosphine oxide or sulphide,[14] [4+2] cycloaddition between anthracene and a 1-alkynylphosphine oxide[15] and palladium-catalysed annulation of 1-alkynylphosphine sulphides with 2-iodoanilines.[16] Alternatively, the biaryl motif of monophosphine oxides[17] and phosphonates[18] have also been prepared directly via palladium-catalyzed cross-coupling of aryl boronic acids with aryl bromides containing ortho $P(O)R_2$ and $P(O)(OR)_2$ groups, respectively, and while the need to reduce the resulting phosphine oxide restricts the range of accessible phosphino groups, phosphonates are versatile and can be transformed into a variety of P-based ligands. Although the overwhelming majority of biaryl monophosphines have been developed for use in achiral transformations, axially chiral biaryl monophosphines have been identified as the ligand of choice for a select number of asymmetric reactions including Suzuki-Miyaura cross-coupling,[18] α-arylation/vinylation of carbonyl enolates,[19] hydrosilylation of olefins[20] and hydrovinylation.[21] These ligands are typically based on either a tri- or tetrasubstituted biaryl unit which often contains an additional heteroatom donor such as $-NR_2$ (KenPhos) or -OMe (MOP) at the 2′-position. While these ligands are commonly prepared from enantiopure biaryl electrophiles via metal-catalyzed phosphination,[22] Buchwald[18a,b] and others[18c-g] have demonstrated that axially chiral biaryl monophosphonates can also be obtained in excellent yield and high ee via asymmetric palladium-catalyzed coupling of aryl halides bearing an ortho phosphonate group with substituted aryl boronic acids; the resulting phosphonates are ideal precursors for diversification into phosphines, phosphinites and phospholanes for use in catalysis. More recently chiral biaryl and heterobiaryl monophosphonates have been prepared in high enantioselectivity via rhodium/BINAP-catalyzed [2+2+2] cycloaddition of symmetrical diynes with 2-substituted naphthylethynyl phosphonates[14a] and QUINAP has been synthesized via an elegant and highly efficient dynamic kinetic resolution involving an atroposelective P-C coupling.[23]

Given the justifiable status of the biaryl architecture as a privileged scaffold,[24] there is still considerable interest in developing alternative approaches to constructing this motif. As part of an on-going programme to develop new ligands for palladium-catalyzed C-C and C-heteroatom bond formation we initiated a study to target novel cross-coupling partners and chose to investigate aryl/naphthyl boronate esters substituted with an ortho phosphonate group on the basis that they represent a new class of nucleophilic coupling partner that could provide access to architecturally important achiral and axially chiral biaryl and heterobiaryl ligands. Herein, we disclose the first examples of Suzuki-Miyaura couplings involving aryl and naphthylphosphonate-based boronate esters as the nucleophilic partner (Equation 1) and that good to excellent yields of tropos and atropos biaryl and heterobiaryl monophosphonates can be obtained using relatively low catalyst loadings. The use of arylphosphonate-based boronate esters as the nucleophilic coupling partner has not previously been reported and could eventually complement/extend existing approaches in which the phosphonate is introduced as the electrophile[18] (Equation 2).



RESULTS AND DISCUSSION

This project was initiated to develop the use of aryl- and naphthylphosphonate-based boronate esters as nucleophilic partners in Suzuki-Miyaura cross coupling reactions and to undertake a systematic comparison of the performance of our KITPHOS monophosphines (**1a**, R = Cy; **1b**, R = Ph) against their biaryl-based counterpart XPHOS. The associated precatalysts **2a-c** (L = **1a**, **2a**; L = **1b**, **2b**; L = XPHOS, **2c**) required for this study were prepared in a straightforward manner by reaction of the corresponding phosphine with the chloride bridged dimer [Pd{κ^2-*N*2′,*C*1-2-(2′-$NH_2C_6H_4$)C_6H_4}(μ-Cl)]$_2$ in a 1/1 mixture of acetone and dichloromethane (Scheme 1).[25]



Scheme 1. Synthesis of KITPHOS and XPHOS-based precatalysts 2a-c.

One-component precatalysts of this type have recently been introduced and promoted by Buchwald as an extremely convenient and efficient source of $L_1Pd(0)$ as they are air- and moisture-stable and readily undergo spontaneous and quantitative reductive elimination of the cyclometalated amine to afford 9H-carbazole upon treatment with base and, in this regard, are markedly more efficient than generating the catalyst in situ from either a source of Pd(0) such as $Pd_2(dba)_3$ or from $Pd(OAc)_2$ and excess phosphine.[26] Precatalyst **2a-c** were purified by column chromatography and characterized by a combination of the usual spectroscopic and analytical techniques. Even though the spectroscopic properties of **2a-b** are similar to those reported for **2c**[27] and therefore fully consistent with the proposed formulation, a single-crystal X-ray analysis of **2b** was also undertaken to compare the key structural features with those of related complexes; a perspective view of the molecular structure is shown in Figure 1. The palladium center adopts a slightly distorted square planar geometry with the phosphine located trans to the amine due to the high trans influence of the strongly σ-donating metalated aromatic ring[28] while the key Pd(1)-P(1), Pd(1)-N(1), Pd(1)-C(1) and Pd(1)-Cl(1) bond lengths are all similar to those in [Pd{κ^2-*N*2′,*C*1-2-(2′-$NH_2C_6H_4$)C_6H_4}(Cl)(L)] (L = SPHOS, XPHOS and dihydro-KITPHOS).[27,29-30]

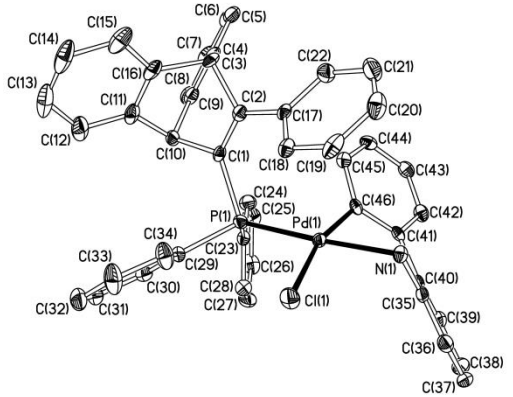
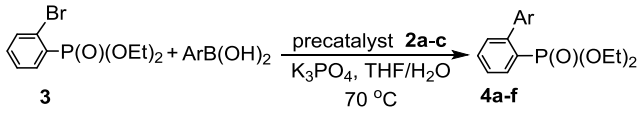


Figure 1. Molecular structure of [Pd{κ^2-*N*2′,*C*1-2-(2′-$NH_2C_6H_4$)C_6H_4}Cl{11-(diphenylphosphino)-12-phenyl-9,10-dihydro-9,10-ethenoanthracene}] (**2b**). Hydrogen atoms have been omitted for clarity. Ellipsoids are drawn at the 50% probability level.

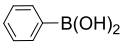
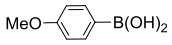
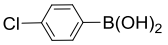
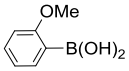
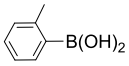
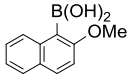
With the aim of developing complementary pathways to biaryl monophosphonates, we began our study by investigating the cross-coupling between diethyl (2-bromophenyl)phosphonate **3** and a selection of commercially available aryl boronic acids, full details of which are presented in Table 1. Our preliminary comparison and optimization focused on the coupling between **3** and benzene boronic acid using 0.1 mol% of precatalysts **2a-c** and identified K_3PO_4 to be the optimum base and THF/H_2O (2:1, v/v) as the solvent of choice. Under these conditions catalyst generated from **2a-c** each gave **4a** in good yield with XPHOS-based **2c** proving to be more efficient than its KITPHOS counterparts **2a** and **2b** (entry 1-3). As such, each substrate combination in this study has been conducted with KITPHOS-based precatalysts **2a-b** as well as **2c** in order to undertake a systematic, thorough and meaningful comparison. Although good conversions were also obtained with 0.1 mol% **2a** in dry THF, under otherwise identical conditions, the presence of added water resulted in consistently higher yields.[31] The choice of base and solvent also proved crucial to achieving good conversions; K_3PO_4 was most effective for

reactions conducted in toluene, while KF and K_3PO_4 were both effective bases for reactions conducted in THF, DME and toluene, K_2CO_3 was more effective in toluene than THF and other bases such as alkali metal acetates and alkoxides were markedly less effective in all solvents.

Table 1. Palladium-Catalyzed Suzuki-Miyaura Coupling of Diethyl (2-bromophenyl)phosphonate with Aryl Boronic Acids[a]



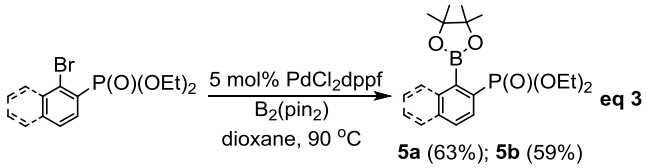
3 4a-f

	Ar-B(OH)$_2$	Precat (mol%)	Time (min)	Product	Yield (%)[b]
1		**2a**/0.1	15	**4a**	83
2		**2b**/0.1	15	**4a**	68
3		**2c**/0.1	15	**4a**	99
4		**2a**/0.1	15	**4b**	92
5		**2b**/0.1	15	**4b**	70
6		**2c**/0.1	15	**4b**	45
7		**2a**/0.1	15	**4c**	98
8		**2b**/0.1	15	**4c**	68
9		**2c**/0.5	15	**4c**	63
10		**2a**/0.5	30	**4d**	97
11		**2b**/0.5	30	**4d**	34
12		**2c**/0.5	30	**4d**	42
13		**2a**/0.5	30	**4e**	98
14		**2b**/0.5	180	**4e**	78
15		**2c**/0.5	30	**4e**	24
16		**2a**/0.5	960	**4f**	6
17		**2b**/0.5	960	**4f**	0
18		**2c**/0.5	960	**4f**	0

[a]Reaction conditions: 0.4 mmol of **3**, 0.6 mmol of boronic acid, 0.8 mmol of K_3PO_4, 0.1-0.5 mol% of **2a-c**, 2 mL THF, 1 mL water, 70 ºC. [b]Isolated yield after purification by column chromatography. Average of three runs.

In contrast to phenyl boronic acid, KITPHOS derived **2a** formed a more efficient catalyst than its XPHOS counterpart for the coupling of substituted aryl boronic acids including 4-methoxyphenyl boronic acid (entries 4-6) and 4-chlorophenyl boronic acid (entries 7-9). For example, 0.1 mol% of **2a** gave **4b** and **4c** in 96% and 98% yield, respectively, after 30 min while the corresponding yields of 45% and 63%, respectively, obtained with **2c** were somewhat lower. The same trend in performance also extended to the sterically more challenging 2-methoxyphenyl boronic acid and *o*-tolyl boronic acid (entries 10-15) as 0.5 mol% of **2a** gave **4d** and **4e** in 97% and 98% yield, respectively, after only 30 min, which were a significant and marked improvement on the corresponding yields of 42% and 24% obtained with its XPHOS counterpart. Interestingly, for each aryl boronic acid tested, reasonable to good yields of product were also obtained with precatalyst **2b**, which was somewhat surprising considering the triaryl-like nature of the monophosphine. However, disappointingly low yields were obtained for the sterically more challenging combination of 2-methoxy-1-naphthylboronic acid and diethyl-(2-bromophenyl)phosphonate even with 2 mol% **2a-c**, which revealed the limitation of these palladacyclic precatalysts for this coupling (entries 16-18).

Encouraged by the efficacy of **2a-c** for the cross-coupling of an arylphosphonate-based electrophile, the study was extended to explore the coupling of aryl and naphthylphosphonate-derived boronate esters as the nucleophilic partner on the basis that this was an entirely new reagent that could further broaden and extend the range of accessible biaryl and heterobiaryl monophosphonates. Phenyl and naphthyl pinacol boronate esters **5a** and **5b**, respectively, were prepared in good yield via the palladium-catalyzed borylation of diethyl (2-bromophenyl)phosphonate and diethyl (1-bromonaphthalen-2-yl)phosphonate, respectively, with $B_2(pin)_2$ in dioxane at 90 °C for 16 h using 5 mol% $PdCl_2(dppf)$ as catalyst (Equation 3).[32] While **5a-b** could also be prepared by reaction of the derived Grignard reagent with $B(OMe)_3$ followed by alcoholysis with pinacol the yields were slightly lower for this multistep sequence.

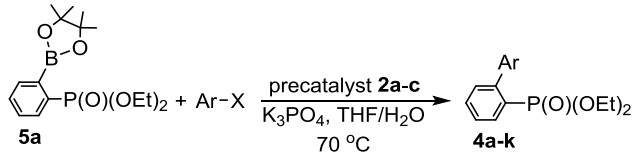


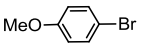
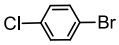
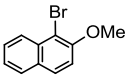
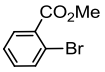
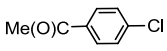
5a (63%); **5b** (59%) **eq 3**

An additional brief optimization study using bromobenzene and **5a** as the benchmark combination with 0.5 mol% of precatalyst **2a**, revealed that the highest conversions were also obtained in THF/water with K_3PO_4 as base at 70 ºC whereas those obtained in DME, dry THF or toluene with the same base were markedly lower. A survey of the base revealed that good conversions could also be obtained in THF/H_2O with Cs_2CO_3 while Na_2CO_3, KF and KOAc all gave poor conversions; full details are provided in Table S1 of the supporting information. As catalyst generated from XPHOS-based **2c** also gave **4a** in high yield (Table 2, entries 1-3), precatalysts **2a-c** were used to explore the range of substrate combinations and undertake comparative catalyst testing. Under these optimum conditions, catalyst generated from 0.5-2.0 mol% of **2a-c** efficiently promoted the coupling between **5a** and a range of electron-rich and electron-poor aryl halides as well as heteroaryl halides to give high yields in relatively short reaction times. The results in Table 2 show that (i) catalyst based on **2a** was consistently more efficient than its diphenylphosphino counterpart **2b** across the entire set of substrates tested, (ii) catalyst generated from **2a** either competed with or outperformed its XPHOS counterpart **2c**, albeit by a relatively small margin in some cases, and (iii) higher catalyst loadings and longer reaction times were required compared with the corresponding couplings involving **3**. For example, catalyst generated from 0.5 mol% of **2a** coupled 4-bromoanisole with **5a** to afford **4b** in 66% yield after 60 min (Table 2, entry 4). whereas the same product was obtained in 92% yield from the reaction between **3** and 4-methoxyphenyl boronic acid after only 15 min using 0.1 mol% of the same precatalyst (Table 1, entry 4). Sterically hindered 2-substituted aryl bromides required longer reaction times to give good yields (Table 2, entries 10-21) and a comparison of catalyst efficacy across this narrow range of substrates underpins the competitive performance of KITPHOS monophosphines against their well-established biaryl counterparts. Precatalysts **2a** and **2c** both effectively promoted the coupling of 2-bromopyridine and 2-bromopyrimidine with **5a** to give the corresponding heterobiaryl monophosphonates **4h** and **4i**, respectively, in good yields after 4 h (Table 2, entries 22-27); in both cases KITPHOS-precatalyst **2a** outperformed **2b** and **2c**. In contrast, **2a** and **2c** gave comparable yields of **4j** from the reaction

between 5-bromopyrimidine and **5a** after 2h at 70 ºC (Table 2, entries 28-30).

Table 2. Palladium-Catalyzed Suzuki-Miyaura Coupling of Aryl Halides with 5a using Precatalysts 2a–c[a]



	Ar-B(OH)$_2$	Precat (mol%)	Time (h)	Product	Yield (%)[b]
1		**2a**/0.5	1	**4a**	69
2		**2b**/0.5	1	**4a**	44
3		**2c**/0.5	1	**4a**	77
4		**2a**/0.5	1	**4b**	66
5		**2b**/0.5	1	**4b**	60
6		**2c**/0.5	1	**4b**	59
7		**2a**/0.5	1	**4c**	90
8		**2b**/0.5	1	**4c**	70
9		**2c**/0.5	1	**4c**	62
10		**2a**/0.5	4	**4d**	60
11		**2b**/0.5	4	**4d**	30
12		**2c**/0.5	4	**4d**	76
13		**2a**/0.5	2	**4e**	91
14		**2b**/0.5	2	**4e**	61
15		**2c**/0.5	2	**4e**	83
16		**2a**/2.0	16	**4f**	56
17		**2b**/2.0	16	**4f**	0
18		**2c**/2.0	16	**4f**	0
19		**2a**/0.5	16	**4g**	40
20		**2b**/0.5	16	**4g**	0
21		**2c**/0.5	16	**4g**	49
22		**2a**/0.5	4	**4h**	91
23		**2b**/0.5	4	**4h**	62
24		**2c**/0.5	4	**4h**	64
25		**2a**/0.5	4	**4i**	91
26		**2b**/0.5	4	**4i**	24
27		**2c**/0.5	4	**4i**	81
28		**2a**/0.5	2	**4j**	50
29		**2b**/0.5	2	**4j**	30
30		**2c**/0.5	2	**4j**	49
31		**2a**/0.5	16	**4k**	41
32		**2c**/0.5	16	**4k**	81

[a]Reaction conditions: 0.2 mmol of Ar-X, 0.3 mmol **5a**, 0.4 mmol of K_3PO_4, 0.5 or 2 mol% **2a-c**, 2 mL THF, 1 mL water, 70 ºC. [b]Isolated yield after purification by column chromatography. Average of three runs.

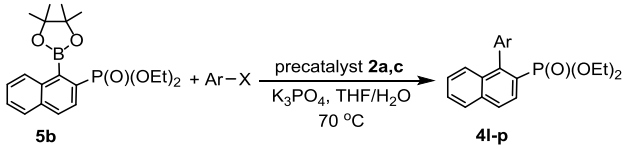
While **2a** formed a highly efficient catalyst for the coupling of aryl and heteroaryl bromides, its XPHOS counterpart proved to be the catalyst of choice to couple 4-chloroacetophenone with **5a** as the yield of 81% obtained after 16 h at 70 ºC with 0.5 mol% of **2c** was markedly higher than that of 41% obtained with **2a** in the same time (Table 2, entries 31-32). With the intention of applying this substrate combination to the synthesis of axially chiral atropisomeric biaryl monophosphonates for further diversification into new biaryl ligands the coupling between 1-bromo-2-methoxynaphthalene and boronate ester **5a** was also investigated. Gratifyingly, phosphonate **4f** was obtained in 56% yield after 16 h at 70 ºC with 2 mol% of palladacycle **2a** (Table 2, entry 16) and even though the yield did not increase with longer reaction times it is a substantial and marked improvement on the corresponding coupling between **3** and 2-methoxy-1-naphthylboronic acid (Table 1, entry 16-18); this promising result underpins the potential benefits of employing arylphosphonate-based boronate esters and their acids as the nucleophilic partner in Suzuki-Miyaura cross couplings.

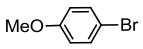
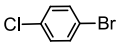
Based on the promising results obtained with **5a** and reasoning that it would be both instructive and informative to have access to an isomeric ligand pair with the phosphonate group located on either the naphthyl fragment or the phenyl ring for comparative catalyst testing the coupling of naphthylphosphonate boronate ester **5b** with a series of aryl and heteroaryl bromides was also examined, details of which are presented in Table 3. This phase of the study focused on the use of precatalysts **2a** and **2c** as they gave the most promising yields for sterically challenging substrate combinations in Table 2. Under the conditions described above, good yields were obtained with electron rich, electron poor, sterically hindered aryl as well as heteroaryl electrophilic partners. For example, **2a** and **2c** formed highly efficient catalysts for the reaction between **5b** and 4-bromoanisole or 4-chloro bromobenzene (Table 3, entries 1-4), interestingly, the latter reaction occurred chemoselectively to afford **4m** with no evidence for activation of the chloride, as evidence by analysis of the crude reaction mixture as well as the purified product by high resolution LCMS; a minor contaminant (<5%) has been identified by NMR spectroscopy and HRMS as diethyl naphthalen-2-ylphosphonate, the product of protodeboronation. Sterically hindered and heteroaryl coupling partners typically required a higher catalyst loading and longer reaction time to reach good conversions. For example, 2 mol% of palladacycle **2a** coupled 2-bromotoluene and 2-bromoanisole with **5b** to give the corresponding atropisomeric monophosphonates **4n** and **4o** in 76% and 77% yield, respectively after 16 h at 70 ºC (Table 3, entries 5 and 7); for comparison **2c** gave the same products in 42% and 87% yield, respectively, under the same conditions (Table 3, entries 6 and 8). Interestingly, the coupling between **5b** and 2-bromoanisole to give **4o** occurs more efficiently than the corresponding 'isomeric coupling' between 2-methoxy-1-bromonaphthalene and phosphonate **5a,** which affords **4f** in 56% yield. Finally, precatalyst **2a** outperformed its XPHOS counterpart for the coupling between 2-bromopyridine and **5b** due to facile competing protodeboronation which presumably becomes more significant in the presence of a less efficient catalyst.[33] In this regard, protodeboration was identified as the only competing pathway for reactions involving **5b**, which became more significant for substrate combinations that required long reaction times. For instance, while the cross coupling between **5b** and either 4-bromoanisole or 4-bromochlorobenzene resulted in 1-4% protodeboronation this increased to 19% and 21% for the corresponding reactions involving 2-bromotoluene and 2-bromoanisole, respectively, with **2a** and **2c** giving the same level of protodeboronation for both substrate combinations. In contrast, the extent of protodeboronation for the reaction between 2-bromopyridine and **5b** was catalyst dependent and much more rapid for **2c** which gave 73% conversion to diethyl naphthalen-2-ylphosphonate compared to only 21% with **2a**.

Thus, in terms of ligand synthesis **5b** appears to be a practical coupling partner as high yields of the corresponding atropos

biaryl/heterobiaryl monophosphonates can be obtained in short reaction times under mild conditions. As monophosphonates **4n** and **4o** are ideal precursors to chiral monophosphines future endeavours will be directed towards developing an asymmetric version of this coupling using KenPHOS and electron-rich MOP-type monophosphines as lead ligands.[18a-g]

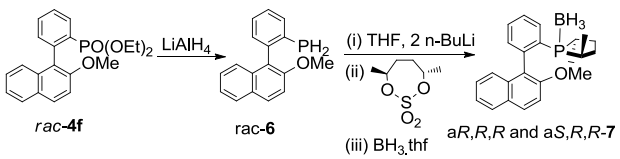
Table 3. Palladium-Catalyzed Suzuki-Miyaura Coupling of Aryl Bromides with 5b using Precatalysts 2a and 2c[a]



	Ar-B(OH)$_2$	Precat (mol%)	Time (h)	Product	Yield (%)[b]
1		**2a**/0.5	2	**4l**	68
2		**2c**/0.5	2	**4l**	53
3		**2a**/0.5	2	**4m**	81[c]
4		**2c**/0.5	2	**4m**	89[c]
5		**2a**/2.0	16	**4n**	76
6		**2c**/2.0	16	**4n**	42
7		**2a**/2.0	16	**4o**	77
8		**2c**/2.0	16	**4o**	87
9		**2a**/1.0	16	**4p**	58
10		**2c**/1.0	16	**4p**	25

[a]Reaction conditions: 0.2 mmol of Ar-Br, 0.3 mmol of **5b**, 0.4 mmol of K_3PO_4, 0.5 or 2 mol% of **2a** or **2c**, 2 mL THF, 1 mL water, 70 ºC. [b]Isolated yield after purification by column chromatography. Average of three runs. [c]Yield adjusted to account for protodeboronation.

As a proof of principle exercise before applying these new coupling partners to the synthesis of monophosphines, *rac*-**4f** was first reduced with $LiAlH_4$ to afford the corresponding primary phosphine as a white air-stable solid in quantitative yield. The ^{31}P NMR spectrum of 6 contains a triplet with a characteristically large $^1J_{PH}$ of 204 Hz while the associated diastereotopic protons appear as a pair of doublets at δ 3.54 and 3.59 ppm in the ^1H NMR spectrum. As primary phosphines are ideal precursors to phospholane-based ligands, **6** was reacted with the cyclic sulphate derived from *R,R*-hexane-2,5-diol by stepwise treatment with *n*-BuLi following previously reported procedures[34] to afford a 1:1 mixture of *aR,R,R*-**7** and *aS,R,R*-**7** in 32% yield, after protection as its borane adduct (Scheme 2). Although moderate, this yield is a marked improvement on that reported for the closely related binaphthyl-based monophospholane 2-phospholano-2′-methoxy-1,1′-binaphthyl.[18d]



Scheme 1

Scheme 2. Synthesis of phospholane *aR,R,R*-7 and *aS,R,R*-7 by reduction of *rac*-4f.

CONCLUSION

In conclusion, the first examples of aryl and naphthylphosphonate-derived boronate esters have been prepared, their use as nucleophilic coupling partners for the palladium-catalysed Suzuki-Miyaura cross-coupling with a range of aryl and heteroaryl bromides investigated and a comparison with the corresponding mutually complementary coupling between aryl halides bearing an ortho phosphonate and aryl or naphthylboronic acids undertaken. Regardless of the source of aryl or naphthylphosphonate (i.e. nucleophile or electrophile) good yields of the corresponding biaryl and heterobiaryl monophosphonates were obtained with Buchwald-type single source KITPHOS and XPHOS precatalysts. Gratifyingly, precatalyst **2a**, based on dicyclohexylphosphino KITPHOS monophosphine **1a,** outperformed its XPHOS counterpart **1c** for several substrate combinations. Taken together, this pair of couplings could provide complementary pathways to achiral and axially chiral biaryl monophosphonates which will enable the substitution pattern of the biaryl architecture to be systematically varied and heteroatom groups to be introduced and ultimately be developed into a practical and valuable tool for the synthesis of ligands as well as bioactive molecules based on the biarylphosphonate motif. Studies are currently underway to prepare a broader range of aryl and naphthylmonophosphonate-based boronate esters in order to expand the scope of this coupling sequence, develop, optimise and apply an asymmetric version of this coupling across an array of aryl and heteroaryl substrate combinations, explore the range of accessible achiral and chiral phosphorus-based ligands that can be prepared either from the phosphonate or its corresponding primary phosphine and extend the phosphonate-based nucleophilic partners to zinc, magnesium and lithium reagents.

EXPERIMENTAL SECTION

General Considerations. All manipulations involving air-sensitive materials were carried out using standard Schlenk line techniques under an atmosphere of nitrogen or argon in oven-dried glassware. Dichloromethane and chloroform were distilled from calcium hydride, THF and toluene from sodium, and hexane and diethyl ether from Na/K alloy, under an atmosphere of nitrogen. Bis(pinacolato)diboron, 1-bromo-2-iodobenzene and diethylphosphite were purchased from commercial suppliers and used without further purification. 1-Bromo-2-methoxynaphthalene,[35] 2-methoxy-1-naphthylboronic acid,[36] diethyl 1-bromo-2-naphthylphosphonate,[18a,b] (2*S*,5*S*)-2,5-hexanediol cyclic sulphate,[33] KITPHOS monophosphines **1a-b**,[15c,d] [$PdCl_2$(1,1-bis(diphenylphosphino)ferrocene]^{37} [Pd{k^2-*N2′,C1*-2-(2′-$NH_2C_6H_4$)C_6H_4}(μ-Cl)]$_2$[25a] and [Pd{k^2-*N2′,C1*-2-(2′-$NH_2C_6H_4$)C_6H_4}Cl(XPHOS)][27b] were prepared as previously described. ^1H, $^{13}C\{^1H\}$ and $^{31}P\{^1H\}$ NMR spectra were recorded on 500 or 400 MHz instruments. Thin-layer chromatography (TLC) was carried out on aluminum sheets pre-coated with silica gel 60F 254, and column chromatography was performed using Merck Kieselgel 60. Gas chromatography-mass spectrometry was performed using a 30 m, 0.25 mm, 0.25μm capillary column, elemental microanalytical data were obtained from the Newcastle University School of Chemistry analytical services unit and electrospray ionization mass spectrometry (ESI-MS) was performed by the Newcastle University School of Chemistry mass spectrometry service.

Synthesis of [Pd{κ^2-*N2′,C1*-2-(2′-$NH_2C_6H_4$)C_6H_4}Cl{11-(dicyclohexylphosphino)-12-phenyl-9,10-dihydro-9,10-ethenoanthracene}] (2a). To a solution of [Pd{k^2-*N2′,C1*-2-(2′-$NH_2C_6H_4$)C_6H_4}(μ-Cl)]$_2$ (0.25 g, 0.405 mmol) in acetone (8–10 mL) was added a solution of **1a** (0.385 g, 0.81 mmol) in

dichloromethane (5–7 mL). After stirring for 2 h, the solvent was removed under reduced pressure and the resulting brown oily residue purified by column chromatography, using CH_2Cl_2/methanol (97/3) as eluant, to give **2a** as a pale yellow spectroscopically pure solid in 81% yield (0.52 g). An analytically pure sample that was also suitable for X-ray structure determination was grown by slow diffusion of a dichloromethane solution layered with hexane at room temperature. Mp: 188 °C (dec). $^{31}P\{^1H\}$ NMR (202.46 MHz, $CDCl_3$, δ): 49.5; ^1H NMR (500.16 MHz, $CDCl_3$, δ): 7.82 (br, 1H, Ar-*H*), 7.46 (br, 1H, Ar-*H*), 7.34 (br, 1H, Ar-*H*), 7.32–7.14 (m, 11H, Ar-*H*), 7.02 (br, 4H, Ar-*H*), 6.96 (t, *J* = 7.3 Hz, 1H, Ar-*H*), 6.58 (t, *J* = 7.3 Hz, 1H, Ar-*H*), 6.15 (t, *J* = 7.3 Hz, 1H, Ar-*H*), 6.10 (t, *J* = 5.5 Hz, 1H, bridgehead C*H*), 5.22 (t, *J* = 2.3 Hz, 1H, bridgehead C*H*), 4.86 (br, 1H, N-*H*), 4.53 (br, 1H, N-*H*), 2.84 (br, 1H, Cy-*H*), 2.21 (br, 1H, Cy-*H*), 1.64 (br, 3H, Cy-*H*), 1.43–1.14 (br, 5H, Cy-*H*), 1.03–0.87 (br, 8H, Cy-*H*), 0.74 (br, 2H, Cy-*H*), 0.23 (br, 1H, Cy-*H*), 0.09 (br, 1H, Cy-*H*); $^{13}C\{^1H\}$ NMR (125.76 MHz, $CDCl_3$, δ): 159.4 (*C*=CP), 148.2 (C_6H_4*Q*), 145.0 (C_6H_4*Q*), 144.7 (C_6H_4*Q*), 144.4 (C_6H_4*Q*), 143.8 (C_6H_4*Q*), 140.4 (d, *J* = 2.0, C_6H_4*Q*), 140.1 (C_6H_4*Q*), 139.3 (C_6H_4*Q*), 135.9 (d, *J* = 8.6 Hz, Ar), 135.2 (d, *J* = 2.1 Hz, C_6H_5*Q*), 134.9 (d, *J* = 29.6 Hz, C=*C*P), 128.7 (Ar*C*H), 128.1 (Ar*C*H), 127.7 (Ar*C*H), 127.6 (Ar*C*H), 126.9 (Ar*C*H), 126.8 (Ar*C*H), 126.3 (Ar*C*H), 125.2 (Ar*C*H), 125.1 (Ar*C*H), 125.0 (br, Ar*C*H), 124.7 (br, Ar*C*H), 123.8 (br, Ar*C*H), 122.9 (br, Ar*C*H), 122.6 (br, Ar*C*H), 120.5 (Ar*C*H), 62.4 (d, *J* = 5.3 Hz, bridgehead *C*H), 56.6 (d, *J* = 12.2 Hz, bridgehead *C*H), 37.4 (d, *J* = 21.9 Hz, Cy-*C*H), 36.2 (d, *J* = 25.3 Hz, Cy-*C*H), 32.4 (Cy-*C*H_2), 30.8 (Cy-*C*H_2), 30.2 (Cy-*C*H_2), 29.8 (Cy-*C*H_2), 28.0 (Cy-*C*H_2), 27.6 (Cy-*C*H_2), 27.5 (Cy-*C*H_2), 27.3 (Cy-*C*H_2), 26.3 (Cy-*C*H_2), 25.9 (Cy-*C*H_2); Anal. Calcd for $C_{46}H_{47}ClNPPd$: C, 70.23; H, 6.02; N, 1.78. Found: C, 70.67; H, 6.44; N, 1.91; LRMS (EI^+) *m/z* 787.2 $[M]^+$.

Synthesis of [Pd{κ^2-*N2′,C1*-2-(2′-$NH_2C_6H_4$)C_6H_4}Cl{11-(diphenylphosphino)-12-phenyl-9,10-dihydro-9,10-ethenoanthracene}] (2b). Compound **2b** was prepared and purified according to the procedure described above for **2a** and isolated as a spectroscopically pure light yellow solid in 75% yield. An analytically pure sample that was also suitable for X-ray structure determination was grown by slow diffusion of a dichloromethane solution layered with methanol at room temperature. Mp: 185 °C (dec). $^{31}P\{H\}$ NMR (161.8 MHz, CH_2Cl_2, δ): 30.9; ^1H NMR (400 MHz, $CDCl_3$, δ): 7.43–6.83 (m, 29H, Ar-*H*), 6.25 (t, *J* = 6.7 Hz, 1H, Ar-*H*), 6.18 (t, *J* = 7.2 Hz, 1H, Ar-*H*), 5.34 (d, *J* = 3.4 Hz, 1H, bridgehead *H*), 5.21 (d, *J* = 7.6 Hz, 1H, bridgehead *H*), 4.77 (br s, 2H, NH_2); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$) δ = 162.3 (d, *J* = 7.7 Hz, *C*CP), 148.1 (C_6H_4 *Q*), 144.8 (2 × C_6H_4 *Q*), 144.4 (2 × C_6H_4 *Q*), 139.9 (C_6H_4 *Q*), 138.5 (C_6H_5 *Q*), 138.4 (C_6H_4 *Q*), 138.4 (C_6H_4 *Q*), 137.4 (C_6H_5), 137.3 (C_6H_5), 135.3 (br, *C*P), 135.3 (C_6H_5), 135.2 (C_6H_5), 130.2 (C_6H_5), 129.7 (br, C_6H_5 *Q*), 127.9 –127.6 (br m, 6 C, 2 × C_6H_5, 4 × C_6H_4), 127.1 (C_6H_4), 127.1 (C_6H_4), 126.0 (C_6H_4), 125.4 (C_6H_4), 125.1 (C_6H_4), 125.0 (C_6H_4), 125.0 (C_6H_4), 123.9 (br, 2 × C_6H_4), 123.1 (2 × C_6H_4), 120.3 (C_6H_4), 60.9 (d, *J* = 7.7 Hz, bridgehead *C*H), 55.4 (d, *J* = 5.5 Hz, bridgehead *C*H), observed complexity due to the presence of rotamers. IR (neat, cm^{-1}) 2981, 1488, 1459, 1158, 1022, 968, 746, 694, 630; Anal. Calcd for $C_{46}H_{35}ClNPPd$: C, 71.32; H, 4.55; N, 1.81. Found: C, 71.78; H, 4.88; N, 2.07; HRMS (ESI^+): exact mass calcd for $C_{46}H_{35}NPClPd$ $[M]^+$ requires *m/z* 773.1230, found *m/z* 773.1208.

Diethyl-2-bromophenylphosphonate (3). A flame-dried Schlenk flask was cooled to room temperature under vacuum, back-filled with nitrogen and charged with $Pd(OAc)_2$ (0.210 g, 0.934 mmol), PPh_3 (2.45 g, 9.34 mmol), EtOH (180 mL), 1-bromo-2-iodobenzene (6.0 mL, 46.7 mmol), diethylphosphite (30 mL, 234 mmol), diisopropylethylamine (51.0 mL, 292 mmol) and the resulting mixture heated at refluxed for 48 h. After this time, the solution was allowed to cool to room temperature then diluted with Et_2O and washed with 1 M HCl (200 mL). The aqueous phase was extracted with Et_2O (3 × 100 mL) and the organic fractions combined, washed with 2.5 M NaOH solution (50 mL), brine (50 mL) then dried over $MgSO_4$, filtered and the solvent removed under reduced pressure. The crude product was purified by column chromatography eluting with hexane:acetone:Et_3N (70:29:1) to give the product as a light yellow oil (8.90 g, 65%). $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 15.4; ^1H NMR (399.78 MHz, $CDCl_3$, δ): 8.02–7.96 (m, 1H, Ar-*H*), 7.66–7.62 (m, 1H, Ar-*H*), 7.40–7.32 (m, 2H, Ar-*H*), 4.22–4.05 (m, 4H, O*C*H_2CH$_3$), 1.33 (t, *J* = 7.1 Hz, 6H, OCH$_2$*C*H_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 136.4 (d, *J* = 8.4 Hz), 134.4 (d, *J* = 11.3 Hz), 133.7 (d, *J* = 2.6 Hz), 129.5 (d, *J* = 192 Hz), 127.0 (d, *J* = 13.6 Hz), 125.3 (d, *J* = 3.8 Hz), 62.7 (d, *J* = 5.4 Hz), 16.4 (d, *J* = 6.6 Hz).

Diethyl [2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl]phosphonate (5a). A flame-dried Schlenk flask was cooled to room temperature under vacuum, back-filled with nitrogen and charged with $Pd(dppf)Cl_2$ (0.25 g, 0.023 mmol), KOAc (0.201 g, 2.05 mmol), bis(pinacolato)diboron (0.260 g, 1.02 mmol), dioxane (4.0 mL), diethyl-2-bromophenylphosphonate. (0.200 g, 0.68 mmol) and the resulting mixture heated at 90 °C for 84 h. After this time the solvent was removed and the crude product purified by column chromatography by using hexane/EtOAc (1:2) as eluent to give the **5a** as a colourless oil in 63% yield (0.147 g). $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 20.5; ^{11}B NMR (128.3 MHz, $CDCl_3$, δ): 30.4; ^1H NMR (399.78 MHz, $CDCl_3$, δ): 7.82 (dd, *J* = 13.1, 7.2 Hz, 1H, C_6H_4P), 7.62–7.58 (m, 1H, C_6H_4P), 7.49 (tt, *J* = 7.4, 1.6 Hz, 1H, C_6H_4P), 7.44 (tdd, *J* = 7.4, 3.9, 1.3 Hz, 1H, C_6H_4P), 4.21–4.02 (m, 4H, O*C*H_2CH$_3$), 1.40 (s, 12H, 4 × CH_3), 1.32 (t, *J* = 7.1 Hz, 6 H, OCH$_2$CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$ δ): 133.5 (d, *J* = 17.3 Hz, C_6H_4P), 132.3 (d, *J* = 11.0 Hz, C_6H_4P), 131.7 (d, *J* = 187 Hz, C_6H_4P), 131.4 (d, *J* = 2.9 Hz, C_6H_4P), 129.2 (d, *J* = 14.6 Hz, C_6H_4P), 84.4 (BO*C Q*), 62.1 (d, *J* = 5.1 Hz, O*C*H_2CH$_3$), 25.0 (4C, *C*H$_3$), 16.5 (d, *J* = 6.6 Hz, OCH$_2$*C*H$_3$), *C*B not detected; IR (neat, cm^{-1}) 1347, 1143, 1019, 962, 761, 564; Anal. Calcd for $C_{16}H_{26}BO_5P$: C, 56.49; H, 7.70. Found: C, 56.81; H, 8.07; HRMS (ESI^+): exact mass calcd for $C_{16}H_{26}O_5BP$ $[M+H]^+$ requires *m/z* 341.1689, found *m/z* 341.1678.

Diethyl 1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-naphthalen-2-ylphosphonate (5b). A flame-dried Schlenk flask was cooled to room temperature under vacuum, back-filled with nitrogen and charged with diethyl 1-bromo-2-naphthylphosphonate (1.50 g, 4.37 mmol), $Pd(dppf)Cl_2$ (0.157 g, 0.215 mmol), KOAc (1.30 g, 13.1 mmol), bis(pinacolato)diboron (1.67 g, 6.65 mmol) and dioxane (20 mL) and the resulting mixture heated to 90 °C for 16 h. The solvent was then removed and the crude product purified by column chromatography with hexane/EtOAc (1:2) as eluent to affords **5b** as a white solid in 59% yield (1.0 g). A spectroscopically and analytically pure crystalline sample was obtained by crystallization from hot *n*-hexane. $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 21.4; ^{11}B NMR (128.3 MHz, $CDCl_3$, δ): 30.1; ^1H NMR (399.78 MHz, $CDCl_3$, δ): 8.09–8.07 (m, 1H, $C_{10}H_6$), 7.86 (dd, *J* = 8.4, 4.0 Hz, 1H, $C_{10}H_6$), 7.83–7.81 (m, 1H, $C_{10}H_6$), 7.72 (dd, *J* = 11.1, 8.4 Hz, 1H, $C_{10}H_6$), 7.54–7.52 (m, 2H, $C_{10}H_6$), 4.23–4.00 (m, 4H, O*C*H_2CH$_3$), 1.54 (s, 12H, 4 × CH_3), 1.30 (t, *J* = 7.1 Hz, 6H, OCH$_2$CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 139.2 (br, C_6H_{10} *C*B), 135.3 (d, *J* = 19.9 Hz, $C_{10}H_6$ *Q*), 134.3 (d, *J* = 2.6 Hz, $C_{10}H_6$ *Q*), 129.4 (d, *J* = 185 Hz, $C_{10}H_6$ *C*P), 129.0 (d, *J* = 14.1 Hz, $C_{10}H_6$), 128.6 ($C_{10}H_6$), 128.4 ($C_{10}H_6$), 127.8 ($C_{10}H_6$), 126.7 ($C_{10}H_6$), 126.6 (d, *J* = 10.7 Hz, $C_{10}H_6$), 84.7 (BO*C Q*), 62.1 (d, *J* = 4.6 Hz, O*C*H_2CH$_3$), 25.8

(4C, *C*H_3), 16.4 (d, *J* = 6.4 Hz, OCH$_2$*C*H$_3$); Mp: 86-88 ^oC; IR (neat, cm^{-1}) 2978, 1288, 1124, 1019, 960, 940, 842, 749, 663, 539; Anal. Calcd for $C_{20}H_{28}BO_5P$: C, 61.56; H, 7.23. Found: C, 61.78; H, 7.52; HRMS (ESI$^+$): exact mass calcd for $C_{20}H_{29}BO_5P$ [M+H]$^+$ requires *m/z* 391.1846, found *m/z* 391.1842.

General Procedure for the Palladium-Catalyzed Suzuki-Miyaura Cross Coupling of Diethyl-(2-bromophenyl)phosphonate with Aryl Boronic Acids. A flame-dried Schlenk flask was cooled to room temperature under vacuum, back-filled with nitrogen and charged with catalyst (2.0 μmol, 0.5 mol% or 0.4 μmol, 0.1 mol%), K_3PO_4 (0.170 g, 0.80 mmol), boronic acid (0.60 mmol) and THF (2.0 mL). Diethyl-(2-bromophenyl)phosphonate (0.117, 0.40 mmol) and water (1.0 mL) were then added and the resulting mixture heated at 70 ºC for the allocated time. After this time, the reaction mixture was cooled to room temperature, diluted with diethyl ether (5 mL) and filtered through a silica plug by flushing with CH_2Cl_2/MeOH (9/1). The solvent was then removed under reduced pressure and the product purified by column chromatography with EtOAc/hexane (2/1) as eluent.

General Procedure for the Palladium-Catalyzed Suzuki-Miyaura Cross Coupling of Diethyl [2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl]phosphonate (5a) with Aryl and Heteroaryl Bromides. A flame-dried Schlenk flask was cooled to room temperature under vacuum, back-filled with nitrogen and charged with catalyst (1 μmol, 0.5 mol% or 4 μmol, 2.0 mol%), K_3PO_4 (0.085 g, 0.40 mmol), [2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl]phosphonate (0.102 g, 0.30 mmol) and THF (2.0 mL). Aryl halide (0.20 mmol) and H_2O (1.0 mL) were then added and the resulting mixture heated at 70 ºC for the allocated time. After this time, the reaction mixture was cooled to room temperature, diluted with diethyl ether (5 mL) and filtered through a silica plug by flushing with CH_2Cl_2/MeOH (9/1). The solvent was then removed under reduced pressure and the product purified by column chromatography with EtOAc/hexane (2/1) as eluent.

General Procedure for the Palladium-Catalyzed Suzuki-Miyaura Cross Coupling between Diethyl 1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-naphthalen-2-ylphosphonate (5b) and Aryl/Heteroaryl Bromides. A flame-dried Schlenk flask was cooled to room temperature under vacuum, back-filled with nitrogen and charged with catalyst (1 μmol, 0.5 mol% or 4 μmol, 2.0 mol%), K_3PO_4 (0.085 g, 0.40 mmol), aryl bromide (0.20 mmol) and diethyl 1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-naphthalen-2-ylphosphonate (0.978 g, 0.3 mmol). THF (2.0 mL), aryl bromide (2.0 mmol) and water (1.0 mL) were added and the resulting mixture heated at 70 ºC for the allocated time. After this time, the reaction mixture was cooled to room temperature, diluted with diethyl ether (5 mL) and filtered through a silica plug by flushing with CH_2Cl_2/MeOH (9/1). The solvent was then removed under reduced pressure and the product purified by column chromatography with EtOAc/hexane (2/1) as eluent.

Diethyl 1,1'-biphenyl-2-ylphosphonate (4a) (Table 1, entries 1-3 and Table 2, entries 1-3): ^{31}P {H} NMR (161.8 MHz, $CDCl_3$, *δ*): 18.7; ^{1}H NMR (400 MHz, $CDCl_3$, *δ*): 7.98 (ddd, *J* = 14.3, 7.7, 1.3 Hz, 1H, C$_6$*H*$_4$P), 7.46 (tt, 7.5, 1.4 Hz, 1H, C$_6$*H*$_4$P), 7.38–7.28 (m, 5H, C$_6$H$_5$, C$_6$*H*$_4$P), 7.24 (ddd, *J* = 7.2, 5.6, 1.1 Hz, 1H, C$_6$*H*$_5$), 3.90–3.71 (m, 4H, OC*H*$_2$CH$_3$), 1.05 (t, *J* = 7.1 Hz, 6H, OCH$_2$C*H*$_3$); ^{13}C{^{1}H} NMR (100.5 MHz, $CDCl_3$, *δ*): 145.8 (d, *J* = 9.8 Hz, C$_6$H$_4$P *Q*), 141.2 (d, *J* = 4.3 Hz, C$_6$H$_5$ *Q*) , 133.6 (d, *J* = 9.7 Hz, C$_6$H$_4$P), 131.8 (d, *J* = 2.7 Hz, C$_6$H$_4$P), 131.2 (d, *J* = 14.0 Hz, C$_6$H$_4$P), 129.1 (2C, C$_6$H$_5$ *m-C*), 127.3 (2C, C$_6$H$_5$ *σ-C*), 126.7 (C$_6$H$_5$ *ρ-C*), 126.7 (d, *J* = 14.0 Hz, C$_6$H$_4$P), 126.7 (d, *J* = 187 Hz, C$_6$H$_4$P *C*P), 61.6 (d, *J* = 6.1 Hz, OC*H*$_2$CH$_3$), 15.9 (d, *J* = 6.8 Hz, OCH$_2$*C*H$_3$); IR (neat, cm^{-1}) 1239, 1018, 958, 754, 700; HRMS (ESI$^+$): exact mass calcd for $C_{16}H_{20}PO_3$ [M+H]$^+$ requires *m/z* 291.1150, found *m/z* 291.1139.

1-(2-Diethoxyphosphorylphenyl)-4-methoxy-benzene (4b) (Table 1, entries 4-6 and Table 2 entries 4-6): ^{31}P{^{1}H} NMR (161.8 MHz, $CDCl_3$, *δ*): 19.0; ^{1}H NMR (400 MHz, $CDCl_3$, *δ*): 7.98 (dd, *J* = 14.1, 7.8 Hz, 1H, C$_6$H$_4$P), 7.48 (t, 7.5 Hz, 1H, C$_6$H$_4$P), 7.38–7.33 (m, 3H, 2 × C$_6$H$_4$OCH$_3$ + C$_6$H$_4$P), 7.27–7.24 (m, 1H, C$_6$*H*$_4$P), 6.89 (d, *J* = 8.7 Hz, 2H, C$_6$*H*$_4$OCH$_3$), 3.9–3.75 (m, 4H, OC*H*$_2$CH$_3$), 3.78 (s, 3H OC*H*$_3$), 1.11 (t, *J* = 7.1 Hz, 6H, OCH$_2$C*H*$_3$); ^{13}C{^{1}H} NMR (100.5 MHz, $CDCl_3$, *δ*): 159.0 (C$_6$H$_4$OCH$_3$ *Q*), 145.7 (d, *J* = 10.0 Hz, C$_6$H$_4$P *Q*), 133.7 (d, *J* = 9.4 Hz, C$_6$H$_4$P), 133.7 (C$_6$H$_4$OCH$_3$ *Q*), 131.9 (d, *J* = 2.7 Hz, C$_6$H$_4$P), 131.5 (d, *J* = 14.2 Hz, C$_6$H$_4$P), 130.4 (2C, C$_6$H$_4$OCH$_3$), 126.8 (d, *J* = 187 Hz, C$_6$H$_4$P *C*P), 126.5 (d, *J* = 14.2 Hz, C$_6$H$_4$P), 112.8 (2 × C$_6$H$_4$OCH$_3$), 61.7 (d, *J* = 6.0 Hz, OC*H*$_2$CH$_3$), 55.2 (OC*H*$_3$), 16.1 (d, *J* = 6.8 Hz, OCH$_2$*C*H$_3$); Mp: 63–64^{o}C; IR (neat, cm^{-1}) 1241, 1021, 956, 763, 552; Anal. Calcd for $C_{17}H_{21}O_4P$: C, 63.74; H, 6.61. Found: C, 64.11; H, 6.79; HRMS (ESI$^+$): exact mass calcd for $C_{17}H_{21}O_4P$ [M+H]$^+$ requires *m/z* 321.1256, found *m/z* 321.1265.

1-(2-Diethoxyphosphorylphenyl)-4-chloro-benzene (4c) (Table 1, entries 7-9 and Table 2, entries 7-9): ^{31}P{^{1}H} NMR (161.8 MHz, $CDCl_3$, *δ*): 18.4; ^{1}H NMR (400 MHz, $CDCl_3$, *δ*): 7.97 (ddd, *J* = 14.5, 7.6, 1.2 Hz, 1H, C$_6$*H*$_4$P), 7.49 (tt, *J* = 7.4, 1.3 Hz, 1H, C$_6$*H*$_4$P), 7.38 (tdd, *J* = 7.5, 3.5, 1.1 Hz, 1H, C$_6$*H*$_4$P), 7.30 (s, 4H, C$_6$*H*$_4$Cl), 7.23–7.20 (m, 1H, C$_6$*H*$_4$P), 3.94–3.77 (m, 4H, OC*H*$_2$CH$_3$), 1.09 (t, *J* = 7.1 Hz, 6H, OCH$_2$C*H*$_3$); ^{13}C{^{1}H} NMR (100.5 MHz, $CDCl_3$, *δ*): 144.9 (d, *J* = 9.6 Hz, C$_6$H$_4$P *Q*), 140.0 (d, *J* = 4.0 Hz, C$_6$H$_4$Cl *Q*), 134.0 (d, *J* = 9.6 Hz, C$_6$H$_4$P), 133.8 (C$_6$H$_4$Cl Q), 132.3 (d, *J* = 2.7 Hz, C$_6$H$_4$P), 131.4 (d, *J* = 13.9 Hz, C$_6$H$_4$P), 130.8 (2C, C$_6$H$_4$Cl), 127.8 (2C, C$_6$H$_4$Cl), 127.4 (d, *J* = 14.7 Hz, C$_6$H$_4$P), 127.1 (d, *J* = 188 Hz, C$_6$H$_4$P *C*P), 62.1 (d, *J* = 5.9 Hz, OC*H*$_2$CH$_3$), 16.2 (d, *J* = 6.7 Hz, OPCH$_2$*C*H$_3$); IR (neat, cm^{-1}) 1232, 1017, 959, 764, 569; Anal. Calcd for $C_{16}H_{18}ClO_3P$: C, 59.18; H, 5.59. Found: C, 59.84; H, 5.96; HRMS (ESI$^+$): exact mass calcd for $C_{16}H_{19}PO_3Cl$ [M+H]$^+$ requires *m/z* 325.0760, found *m/z* 325.0748.

1-(2-Diethoxyphosphorylphenyl)-2-methoxy-benzene (4d) (Table 1, entries 10-12 and Table 2, entries 10-12): ^{31}P{^{1}H} NMR (161.8 MHz, $CDCl_3$, *δ*): 18.7; ^{1}H NMR (400 MHz, $CDCl_3$, *δ*): 8.03 (ddd, *J* = 14.2, 7.7, 1.3 Hz, 1H, C$_6$*H*$_4$P), 7.50 (tt, 7.5, 1.5 Hz, 1H, C$_6$*H*$_4$P), 7.39 (tdd, *J* = 7.5, 3.6, 1.2 Hz, 1H, C$_6$*H*$_4$P), 7.32 (td, *J* = 8.1, 1.7 Hz, 1H, C$_6$*H*$_4$OCH$_3$), 7.28–7.24 (m, 1H, C$_6$*H*$_4$P), 7.21 (dd, *J* = 7.4, 1.7 Hz, 1H, C$_6$*H*$_4$OCH$_3$), 6.95 (dt, *J* = 7.4, 0.8 Hz, 1H, C$_6$*H*$_4$OCH$_3$), 6.91 (d, *J* = 8.3 Hz, 1H, C$_6$*H*$_4$OCH$_3$), 3.93–3.75 (m, 4H, OC*H*$_2$CH$_3$), 3.69 (s, 3 H, OC*H*$_3$), 1.12 (t, *J* = 7.0 Hz, 3 H, OCH$_2$C*H*$_3$), 1.11 (t, *J* = 7.0 Hz, 3H, PCH$_2$C*H*$_3$); ^{13}C{^{1}H} NMR (100.5 MHz, $CDCl_3$, *δ*): 156.6 (C$_6$H$_4$OCH$_3$ *Q*), 142.3 (d, *J* = 9.4 Hz, C$_6$H$_4$P *Q*), 133.7 (d, *J* = 10.0 Hz, C$_6$H$_4$P) , 131.8 (d, *J* = 14.1 Hz, C$_6$H$_4$P), 131.5 (d, *J* = 2.5 Hz, C$_6$H$_4$P), 131.4 (C$_6$H$_4$OCH$_3$), 129.9 (d, *J* = 3.9 Hz, C$_6$H$_4$OCH$_3$ *Q*), 129.0 (C$_6$H$_4$OCH$_3$), 127.6 (d, *J* = 187 Hz, C$_6$H$_4$P *C*P), 126.8 (d, *J* = 14.9 Hz, C$_6$H$_4$P), 119.5 (C$_6$H$_4$OCH$_3$), 110.2 (C$_6$H$_4$OCH$_3$), 61.6 (t, *J* = 6.1 Hz, O*C*H$_2$CH$_3$), 55.3 (OC*H*$_3$), 16.1 (t, *J* = 6.7 Hz, OCH$_2$*C*H$_3$); IR (neat, cm^{-1}) 1230, 1019, 959, 748, 554; Anal. Calcd for $C_{17}H_{21}O_4P$: C, 63.74; H, 6.61. Found: C, 64.24; H, 6.92; HRMS (ESI$^+$): exact mass calcd for $C_{17}H_{21}O_4P$ [M+H]$^+$ requires *m/z* 321.1256, found *m/z* 321.1270.

1-(2-Diethoxyphosphorylphenyl)-2-methyl-benzene (4e) (Table 1, entries 13-15 and Table 2 entries 13-15): ^{31}P{^{1}H}

NMR (161.8 MHz, $CDCl_3$, δ): 18.3; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.04 (ddd, J = 14.2, 7.8, 1.3 Hz, 1H, C_6H_4P), 7.54 (tt, J = 7.6, 1.4 Hz, 1H, C_6H_4P), 7.43 (tdd, J = 7.5, 3.7, 1.2 Hz, 1H, C_6H_4P), 7.25–7.17 (m, 5H, $C_6H_4CH_3$ + C_6H_4P), 3.95–3.69 (m, 4H, OCH_2CH_3), 2.05 (s, 3H, CH_3), 1.16 (t, J = 7.1 Hz, 3H, OCH_2CH_3), 1.12 (t, J = 7.1 Hz, 3 H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 145.4 (d, J = 9.8 Hz, C_6H_4P *Q*), 140.7 (d, J = 3.9 Hz, $C_6H_4CH_3$ *Q*), 136.3 ($C_6H_4CH_3$ *Q*), 133.6 (d, J = 10.3 Hz, C_6H_4P), 131.9 (d, J = 2.7 Hz, C_6H_4P), 131.1 (d, J = 14.4 Hz, C_6H_4P), 130.0 ($C_6H_4CH_3$), 129.5 ($C_6H_4CH_3$), 127.7 ($C_6H_4CH_3$), 127.6 (d, J = 190 Hz, C_6H_4P *C*P), 126.9 (d, J = 14.9 Hz, C_6H_4P), 124.6 ($C_6H_4CH_3$), 61.8 (t, J = 6.2 Hz, OCH_2CH_3), 20.4 (CH_3), 16.3 (d, J = 6.6 Hz, OCH_2CH_3), 16.2 (d, J = 6.7 Hz, OCH_2CH_3); IR (neat, cm^{-1}) 1240, 1017, 958, 766, 552; HRMS (ESI$^+$): exact mass calcd for $C_{17}H_{21}O_3P$ $[M+H]^+$ requires *m/z* 305.1307, found *m/z* 305.1304.

2-Methoxy-1-(2′ -diethoxyphosphorylphenyl)naphthylene (4f) (Table 1, entries 16-18 and Table 2, entries 16-18): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 18.3; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.19 (dd, J = 14.2, 7.7 Hz, 1H, C_6H_4P), 7.88 (d, J = 9.1 Hz, 1H, $C_{10}H_6OCH_3$), 7.79–7.77 (m, 1H, $C_{10}H_6OCH_3$), 7.63 (tt, J = 7.4, 1.3 Hz, 1H, C_6H_4P), 7.54–7.49 (m, 1H, C_6H_4P), 7.34 (d, J = 9.1 Hz, 1H, $C_{10}H_6OCH_3$), 7.30–7.24 (m, 3 H, $C_{10}H_6OCH_3$ + C_6H_4P), 7.12–7.10 (m, 1H, $C_{10}H_6OCH_3$), 3.83 (s, 3H, OCH_3), 3.80–3.49 (m, 4H, OCH_2CH_3), 0.96 (t, J = 7.1 Hz, 3H, OCH_2CH_3), 0.71 (t, J = 7.1 Hz, 3H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 154.1 ($C_{10}H_6OCH_3$ *Q*), 140.6 (d, J = 8.9 Hz, C_6H_4P *Q*), 134.3 (d, J = 10.0 Hz, C_6H_4P), 134.1 ($C_{10}H_6OCH_3$ *Q*), 132.2 (C_6H_4P), 132.2 (d, J = 11.2 Hz, C_6H_4P), 129.5 ($C_{10}H_6OCH_3$), 129.3 (d, J = 189 Hz, C_6H_4P *C*P), 128.4 ($C_{10}H_6OCH_3$ *Q*), 127.6 ($C_{10}H_6OCH_3$), 127.1 (d, J = 14.7 Hz, C_6H_4P), 125.9 ($C_{10}H_6OCH_3$), 125.6 ($C_{10}H_6OCH_3$), 123.7 (d, J = 3.8 Hz, $C_{10}H_6OCH_3$ *Q*), 123.2 ($C_{10}H_6OCH_3$), 112.9 ($C_{10}H_6OCH_3$), 61.6 (d, J = 5.7 Hz, OCH_2CH_3), 61.4 (d, J = 6.0 Hz, OCH_2CH_3), 56.2 (OCH_3), 16.0 (d, J = 6.6 Hz, OCH_2CH_3), 15.5 (d, J = 7.0 Hz, PCH_2CH_3); Mp: 128–129 ^{o}C; IR (neat, cm^{-1}) 1234, 1020, 966, 771, 750, 559; Anal. Calcd for $C_{21}H_{23}O_4P$: C, 68.10; H, 6.26. Found: C, 68.41; H, 6.56; HRMS (ESI$^+$): exact mass calcd for $C_{21}H_{23}PO_4$ $[M+Na]^+$ requires *m/z* 393.1232, found *m/z* 393.1234.

Methyl (2′-diethoxyphosphorylphenyl [1,1′-biphenyl])-2-benzoate (4g) (Table 2, entries 19-21): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 18.8; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.04 (dd, J = 7.8, 1.4 Hz, 1H, $C_6H_4CO_2CH_3$), 8.01 (ddd, J = 14.3, 7.7, 1.3 Hz, 1H, C_6H_4P), 7.56–7.52 (m, 1H, C_6H_4P), 7.50 (dd, J = 7.5, 1.4 Hz, 1H, $C_6H_4CO_2CH_3$), 7.45 (dd, J = 7.7, 1.3 Hz, 1H, $C_6H_4CO_2CH_3$), 7.45–7.41 (m, 1H, C_6H_4P), 7.30 (dd, J = 7.6 Hz, 1.3 Hz, 1H, $C_6H_4CO_2CH_3$), 7.23–7.20 (m, 1H, C_6H_4P), 3.94–3.71 (m, 4H, OCH_2CH_3), 3.57 (s, 3H, OCH_3), 1.10 (q, J = 6.9 Hz, 6H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 167.2 (*C*O), 145.7 (d, J = 8.9 Hz, C_6H_4P *Q*), 142.4 (d, J = 4.0 Hz, $C_6H_4CO_2CH_3$ *Q*), 133.3 (d, J = 9.9 Hz, C_6H_4P), 131.6 (d, J = 2.7 Hz, C_6H_4P), 131.5 ($C_6H_4CO_2CH_3$), 131.0 ($C_6H_4CO_2CH_3$), 130.2 (d, J = 14.2 Hz, C_6H_4P), 130.0 ($C_6H_4CO_2CH_3$), 130.0 ($C_6H_4CO_2CH_3$ *Q*), 127.8 ($C_6H_4CO_2CH_3$), 126.8 (d, J =14.9 Hz, C_6H_4P), 126.3 (d, J = 187 Hz, C_6H_4P *C*P), 61.9 (d, J = 6.1 Hz, OCH_2CH_3), 61.6 (d, J = 5.8 Hz, OCH_2CH_3), 51.8 (OCH_3), 16.2–16.1 (m, OCH_2CH_3); IR (neat, cm^{-1}) 1721, 1239, 1025, 957, 777, 765, 551; Anal. Calcd for $C_{18}H_{21}O_4P$: C, 65.05; H, 6.37. Found: C, 65.19; H, 6.59; HRMS (ESI$^+$): exact mass calcd for $C_{18}H_{22}O_5P$ $[M+H]^+$ requires *m/z* 349.1205, found *m/z* 349.1217.

Diethyl (2-(pyridin-2-yl)phenyl)phosphonate (4h) (Table 2, entries 22-24): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 18.4; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.62 (d, J = 4.9 Hz, 1H, C_5H_4N), 7.98 (dd, J = 14.2, 7.7 Hz, 1H, C_6H_4P), 7.69 (t, 7.6 Hz, 1H, C_5H_4N), 7.60 (d, J = 8.2 Hz, 1H, C_5H_4N), 7.56 (d, J = 7.5 Hz, 1H, C_6H_4P), 7.49–7.44 (m, 2H, C_6H_4P), 7.26–7.23 (m, 1H, C_5H_4N), 3.96–3.83 (m, 4H, OCH_2CH_3), 1.10 (t, J = 7.0 Hz, 6H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 158.9 (d, J = 4.5 Hz, C_5H_4N *Q*), 148.8 (C_5H_4N), 144.7 (d, J = 9.9 Hz, C_6H_4P *Q*), 135.6 (C_5H_4N), 133.8 (d, J = 9.3 Hz, C_6H_4P), 132.2 (d, J = 2.5 Hz, C_6H_4P), 130.9 (d, J = 13.6 Hz, C_6H_4P), 127.9 (d, J = 14.3 Hz, C_6H_4P), 126.5 (d, J = 186 Hz, C_6H_4P *C*P), 124.7 (C_6H_4N), 122.4 (C_6H_4N), 62.0 (t, J = 5.8 Hz, OCH_2CH_3), 16.1 (d, J = 7.0 Hz, OCH_2CH_3); Mp: 74–76^{o}C; IR (neat, cm^{-1}) 1259, 1083, 1011, 794, 753; Anal. Calcd for $C_{15}H_{18}NO_3P$: C, 61.85; H, 6.23; N, 4.81. Found: C, 62.17; H, 6.43; N, 5.18; HRMS (ESI$^+$): exact mass calcd for $C_{15}H_{18}O_3NP$ $[M+H]^+$ requires *m/z* 292.1103, found *m/z* 292.1097.

Diethyl (2-(pyrimid-2-yl)phenyl)phosphonate (4i) (Table 2, entries 25-27): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 18.0; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.82 (d, J = 5.0 Hz, 2H, $C_4H_3N_2$), 7.99 (dd, J = 14.3, 7.3 Hz, 1H, C_6H_4P), 7.75–7.72 (m, 1H, C_6H_4P), 7.62 (t, J = 7.6 Hz, 1H, C_6H_4P), 7.53 (tdd, J = 7.7, 3.6, 1.2 Hz, 1H, C_6H_4P), 7.28 (t, J = 4.8 Hz, 1H, $C_4H_3N_2$), 4.11–3.95 (m, 4 H, OCH_2CH_3), 1.22 (t, J = 7.1 Hz, 6H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 167.1 (d, J = 4.8 Hz, $C_4H_3N_2$ *Q*), 156.7 (2C, $C_4H_3N_2$), 143.5 (d, J = 9.4 Hz, C_6H_4P *Q*), 133.9 (d, J = 8.5 Hz, C_6H_4P), 132.2 (d, J = 2.7 Hz, C_6H_4P), 130.6 (d, J = 13.1 Hz, C_6H_4P), 128.9 (d, J = 14.0 Hz, C_6H_4P), 127.3 (d, J = 187 Hz, C_6H_4P *C*P), 119.5 ($C_4H_3N_2$), 62.2 (d, J = 5.7 Hz, OCH_2CH_3), 16.3 (t, J = 6.7 Hz, OCH_2CH_3); IR (neat, cm^{-1}) 1557, 1413, 1233, 1018, 958, 759, 566; Anal. Calcd for $C_{14}H_{17}N_2O_3P$: C, 57.53; H, 5.86; N, 9.58. Found: C, 57.98; H, 6.22; N, 9.89; HRMS (ESI$^+$): exact mass calcd for $C_{14}H_{18}O_3N_2P$ $[M+H]^+$ requires *m/z* 293.1055, found *m/z* 293.1066.

Diethyl (2-(pyrimid-5-yl)phenyl)phosphonate (4j) (Table 2, entries 28-30):. $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 17.6; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 9.22 (s, 1H, $C_4H_3N_2$), 8.76 (s, 2H, $C_4H_3N_2$), 8.11 (dd, J = 14.5, 7.6 Hz, 1H, C_6H_4P), 7.64 (t, 7.6 Hz, 1H, C_6H_4P), 7.55 (td, J = 7.7, 3.6 Hz, 1H, C_6H_4P), 7.32–7.29 (m, 1H, C_6H_4P), 4.00–3.89 (m, 4H, OCH_2CH_3), 1.16 (t, J = 7.1 Hz, 6H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 157.7 ($C_4H_3N_2$), 156.5 (2 x $C_4H_3N_2$), 138.3 (d, J = 8.7 Hz, C_6H_4P *Q*), 135.2 (d, J = 4.1 Hz, $C_4H_3N_2$ *Q*), 134.3 (d, J = 9.6 Hz, C_6H_4P), 132.6 (d, J = 2.5 Hz, C_6H_4P), 131.3 (d, J = 13.5 Hz, C_6H_4P), 128.7 (d, J = 14.5 Hz, C_6H_4P), 128.1 (d, J = 187.2 Hz, C_6H_4P *C*P), 62.3 (d, J = 6.1 Hz, OCH_2CH_3), 16.3 (d, J = 6.4 Hz, OCH_2CH_3); IR (neat, cm^{-1}) 1408, 1238, 1015, 963, 573; Anal. Calcd for $C_{14}H_{17}N_2O_3P$: C, 57.53; H, 5.86; N, 9.58. Found: C, 57.78; H, 6.06; N, 10.03; HRMS (ESI$^+$): exact mass calcd for $C_{14}H_{18}O_3N_2P$ $[M+H]^+$ requires *m/z* 293.1055, found *m/z* 293.1068.

1-(2-Diethoxyphosphorylphenyl)-4-acetophenone (4k) (Table 2, entries 31-32): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 18.2; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.02 (ddd, J = 15.1, 8.1, 1.3 Hz, 1H, C_6H_4P), 7.97 (d, J = 8.3 Hz, 2H, $C_6H_4COCH_3$), 7.56 (tt, J = 7.6, 1.2 Hz, 1H, C_6H_4P), 7.52 (d, J = 8.3 Hz, 2H, $C_6H_4COCH_3$), 7.45 (tdd, J = 7.6, 3.5, 1.2 Hz, 1H, C_6H_4P), 7.30–7.27 (m, 1H, C_6H_4P), 3.97–3.80 (m, 4H, OCH_2CH_3), 2.62 (s, 3H, CH_3), 1.11 (t, J = 7.1 Hz, 6H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 198.0 (*C*O), 146.4 (d, J = 4.1 Hz, $C_6H_4COCH_3$ *Q*), 144.8 (d, J = 9.6 Hz, C_6H_4P *Q*), 136.1 ($C_6H_4COCH_3$ *Q*), 133.9 (d, J = 9.4 Hz, C_6H_4P), 132.2 (d, J = 2.6 Hz, C_6H_4P), 131.0 (d, J = 14.0 Hz, C_6H_4P), 129.7 (2 × $C_6H_4COCH_3$), 127.6 (2C, $C_6H_4COCH_3$), 127.6 (d, J = 14.6 Hz, C_6H_4P), 126.9 (d, J = 187 Hz, C_6H_4P *C*P), 62.0 (t, J = 6.0 Hz, OCH_2CH_3), 26.8 (CH_3), 16.2 (d, J = 6.6 Hz, OCH_2CH_3); Mp: 78–79 ^{o}C; IR (neat, cm^{-1}) 1680, 1230, 1046, 1019, 960, 767, 569; Anal. Calcd for $C_{18}H_{21}O_4P$: C, 65.05; H, 6.37. Found: C, 65.44; H, 6.63; HRMS (ESI$^+$) exact mass

calculated for $C_{18}H_{22}O_4P$ $[M+H]^+$ requires *m/z* = 333.1256, found *m/z* = 333.1268.

Diethyl (1-(4'-methoxyphenyl)-2-naphthyl)phosphonate (4l) (Table 3, entries 1-2): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 19.0; ^1H NMR (400 MHz, $CDCl_3$, δ): 8.07 (dd, *J* = 12.1, 8.6 Hz, 1H, $C_{10}H_6P$), 7.93–7.90 (m, 1H, $C_{10}H_6P$), 7.88 (d, *J* = 8.5 Hz, 1H, $C_{10}H_6P$), 7.54 (t, *J* = 7.4 Hz, 1H, $C_{10}H_6P$), 7.50 (d, *J* = 8.5 Hz, 1H, $C_{10}H_6P$), 7.41–7.37 (m, 1H, $C_{10}H_6P$), 7.29 (d, *J* = 8.6 Hz, 2H, $C_6H_4OCH_3$), 7.01 (d, *J* = 8.6 Hz, 2 H, $C_6H_4OCH_3$), 4.00–3.82 (m, 4H, OCH_2CH_3), 3.90 (s, 3H, OCH_3), 1.20 (t, *J* = 7.1 Hz, 6H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 159.3 ($C_6H_4OCH_3$ *Q*), 145.4 (d, *J* = 10.4 Hz, $C_{10}H_6P$ *Q*), 135.2 (d, *J* = 2.5 Hz, $C_{10}H_6P$ *Q*), 133.5 (d, *J* = 16.1 Hz, $C_{10}H_6P$ *Q*), 131.8 (2 × $C_6H_4OCH_3$), 130.5 (d, *J* = 5.7 Hz, $C_6H_4OCH_3$ *Q*), 128.4 (d, *J* = 10.1 Hz, $C_{10}H_6P$), 127.9 ($C_{10}H_6P$), 127.8 ($C_{10}H_6P$), 127.8 ($C_{10}H_6P$), 127.3 (d, *J* = 14.4 Hz, $C_{10}H_6P$), 126.6 ($C_{10}H_6P$), 125.1 (d, *J* = 188 Hz, $C_{10}H_6P$ *C*P), 113.0 (2C, $C_6H_4OCH_3$), 61.8 (d, *J* = 6.0 Hz, OCH_2CH_3), 55.4 (OCH_3), 16.3 (d, *J* = 6.7 Hz, OCH_2CH_3); Mp: 105°C; IR (neat, cm^{-1}) = 1237, 1021, 972, 956; Anal. Calcd for $C_{21}H_{23}O_4P$: C, 68.10; H, 6.26. Found: C, 68.43; H, 6.54; HRMS (ESI^+): exact mass calcd for $C_{21}H_{24}O_4P$ $[M+H]^+$ requires *m/z* 371.1412, found *m/z* 371.1397.

Diethyl (1-(4'-chlorophenyl)-2-naphthyl)phosphonate (4m) (Table 3, entries 3-4): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 18.6; ^1H NMR (400 MHz, $CDCl_3$, δ): 8.07 (dd, *J* = 12.1, 8.6 Hz, 1H, $C_{10}H_6P$), 7.95 (dd, *J* = 8.6, 3.7 Hz, 1H, $C_{10}H_6P$), 7.90 (d, *J* = 8.2 Hz, 1H, $C_{10}H_6P$), 7.57 (ddd, *J* = 8.1, 5.0, 2.9 Hz, 1H, $C_{10}H_6P$), 7.46 (d, *J* = 8.3 Hz, 2H, C_6H_4Cl), 7.42–7.41 (m, 2H, $C_{10}H_6P$), 7.31 (d, *J* = 8.3 Hz, 2H, C_6H_4Cl), 4.02–3.84 (m, 4H, OCH_2CH_3), 1.20 (t, *J* = 7.1 Hz, 6H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 144.0 (d, *J* = 9.9 Hz, $C_{10}H_6P$ *Q*), 136.9 (d, *J* = 5.2 Hz, C_6H_4Cl *Q*), 135.1 (d, *J* = 2.4 Hz, $C_{10}H_6P$ *Q*), 133.9 (C_6H_4Cl *Q*), 132.9 (d, *J* = 15.7 Hz, $C_{10}H_6P$ *Q*), 132.1 (2C, C_6H_4Cl), 128.3 (d, *J* = 9.7 Hz, $C_{10}H_6P$), 128.1 ($C_{10}H_6P$), 128.0 ($C_{10}H_6P$), 127.8 (d, *J* = 14.0 Hz, $C_{10}H_6P$), 127.8 (2C, C_6H_4Cl), 127.5 ($C_{10}H_6P$), 126.9 ($C_{10}H_6P$), 125.1 (d, *J* = 188 Hz, $C_{10}H_6P$ *C*P), 62.0 (d, *J* = 5.9 Hz, OCH_2CH_3), 16.3 (d, *J* = 6.7 Hz, OCH_2CH_3); Mp: 60–61°C; IR (neat, cm^{-1}) = 1241, 1049, 1016, 955, 818, 749, 666, 566; Anal. Calcd for $C_{20}H_{20}ClO_3P$: C, 64.09; H, 5.28. Found: C, 64.61; H, 5.65; HRMS (ESI^+): exact mass calcd for $C_{20}H_{20}NaO_3P$ $[M+Na]^+$ requires *m/z* 397.0736, found *m/z* 397.0732.

Diethyl (1-(2′-methylphenyl)-2-naphthyl)phosphonate (4n) (Table 3, entries 5-6): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 18.6; ^1H NMR (400 MHz, $CDCl_3$, δ): 8.09 (dd, *J* = 12.1, 8.6 Hz, 1H, $C_{10}H_6P$), 7.94–7.92 (m, 1H, $C_{10}H_6P$), 7.90 (d, *J* = 8.6 Hz, 1H, $C_{10}H_6P$), 7.55 (t, *J* = 7.44 Hz, 1H, $C_{10}H_6P$), 7.39–7.28 (m, 5H, $C_{10}H_6P$ + $C_6H_4CH_3$), 7.21 (d, *J* = 6.8 Hz, 1H, $C_6H_4CH_3$), 3.99–3.73 (m, 4H, OCH_2CH_3), 1.92 (s, 3H, CH_3), 1.19 (t, *J* = 7.1 Hz, 3H, OCH_2CH_3), 1.17 (t, *J* = 7.1 Hz, 3H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 145.0 (d, *J* = 10.0 Hz, $C_{10}H_6P$ *Q*), 137.9 (d, *J* = 5.2 Hz, $C_6H_4CH_3$ *Q*), 137.7 ($C_6H_4CH_3$ *Q*), 135.1 (d, *J* = 2.5 Hz, $C_{10}H_6P$ *Q*), 132.5 (d, *J* = 16.3 Hz, $C_{10}H_6P$ *Q*), 130.8 ($C_6H_4CH_3$), 129.4 (2C, $C_6H_4CH_3$), 128.4 (d, *J* = 10.3 Hz, $C_{10}H_6P$), 128.1 ($C_{10}H_6P$), 127.9 ($C_{10}H_6P$), 127.4 (d, *J* = 14.5 Hz, $C_{10}H_6P$), 127.2 ($C_{10}H_6P$), 126.9 ($C_{10}H_6P$), 125.0 ($C_6H_4CH_3$), 125.0 (d, *J* = 190 Hz, $C_{10}H_6P$ *C*P), 62.0 (d, *J* = 6.5 Hz, OCH_2CH_3), 61.9 (d, *J* = 6.0 Hz, OCH_2CH_3), 20.1 (CH_3), 16.4 (d, *J* = 6.6 Hz, OCH_2CH_3), 16.2 (d, *J* = 6.8 Hz, OCH_2CH_3); IR (neat, cm^{-1}) = 1241, 1049, 1020, 955, 753, 649, 570, 533; Anal. Calcd for $C_{21}H_{23}O_3P$: C, 71.17; H, 6.54. Found: C, 71.59; H, 6.87; HRMS (ESI^+): exact mass calcd for $C_{21}H_{24}O_3P$ $[M+H]^+$ requires *m/z* 355.1463, found *m/z* 343.1452.

Diethyl (1-(2'-methoxyphenyl)-2-naphthyl)phosphonate (4o) (Table 3, entry 7-8): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 19.0; ^1H NMR (400 MHz, $CDCl_3$, δ): 8.11 (dd, *J* = 12.0, 8.6 Hz, 1H, $C_{10}H_6P$), 7.92 (dd, *J* = 8.6, 3.7 Hz, 1H, $C_{10}H_6P$), 7.88 (d, *J* = 8.2 Hz, 1H, $C_{10}H_6P$), 7.53 (ddd, *J* = 8.1, 6.0, 1.9 Hz, 1H, $C_{10}H_6P$), 7.47–7.43 (m, 1H, $C_6H_4OCH_3$), 7.41–7.35 (m, 2H, $C_{10}H_6P$), 7.23 (dd, *J* = 7.4, 1.7 Hz, 1H, $C_6H_4OCH_3$), 7.07 (td, *J* = 7.5, 1.0 Hz, 1H, $C_6H_4OCH_3$), 7.01 (d, *J* = 8.3 Hz, 1H, $C_6H_4OCH_3$), 4.00–3.78 (m, 4H, OCH_2CH_3), 3.64 (s, 3H, OCH_3), 1.17 (t, *J* = 7.0 Hz, 3H, OCH_2CH_3), 1.16 (t, *J* = 7.0 Hz, 3H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 157.6 ($C_6H_4OCH_3$ *Q*), 142.6 (d, *J* = 9.6 Hz, $C_{10}H_6P$ *Q*), 135.0 (d, *J* = 2.2 Hz, $C_{10}H_6P$ *Q*), 132.9 (d, *J* = 15.9 Hz, $C_{10}H_6P$ *Q*), 132.3 ($C_6H_4OCH_3$), 129.6 ($C_6H_4OCH_3$), 128.7 (d, *J* = 10.2 Hz, $C_{10}H_6P$), 128.0 ($C_{10}H_6P$), 127.8 ($C_{10}H_6P$), 127.4 (d, *J* = 14.4 Hz, $C_{10}H_6P$), 127.4 ($C_{10}H_6P$), 127.2 (d, *J* = 5.2 Hz, $C_6H_4OCH_3$ *Q*), 126.5 ($C_{10}H_6P$), 125.1 (d, *J* = 188 Hz, $C_{10}H_6P$ *C*P), 120.0 ($C_6H_4OCH_3$), 110.2 ($C_6H_4OCH_3$), 61.9 (d, *J* = 5.5 Hz, OCH_2CH_3), 61.7 (d, *J* = 5.9 Hz, OCH_2CH_3), 55.4 (OCH_3), 16.3 (d, *J* = 6.7 Hz, OCH_2CH_3), 16.2 (d, *J* = 6.7 Hz, OCH_2CH_3); Mp: 60–61°C; IR (neat, cm^{-1}) 1226, 1212, 1047, 1021, 974, 754, 648; Anal. Calcd for $C_{21}H_{23}O_4P$: C, 68.10; H, 6.26. Found: C, 68.37; H, 6.47; HRMS (ESI^+): exact mass calcd for $C_{21}H_{23}O_4P$ $[M+H]^+$ requires *m/z* 371.1412, found *m/z* 371.1412.

Diethyl (1-(2'-pyridyl)-2-naphthyl)phosphonate (4p) (Table 3, entries 9-10): $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): 18.5; ^1H NMR (400 MHz, $CDCl_3$, δ): 8.77 (d, *J* = 4.9 Hz, 1H, C_5H_4N), 8.06 (dd, *J* = 11.8, 8.5 Hz, 1H, $C_{10}H_6P$), 7.98 (dd, *J* = 8.6, 3.8 Hz, 1H, $C_{10}H_6P$), 7.91 (d, *J* = 8.2 Hz, 1H, $C_{10}H_6P$), 7.84 (td, *J* = 7.7, 1.8 Hz, 1H, C_5H_4N), 7.58–7.53 (m, 2H, $C_{10}H_6P$, C_6H_4N), 7.43–7.39 (m, 2H, $C_{10}H_6P$, C_6H_4N), 7.33 (d, *J* = 8.5 Hz, 1H, $C_{10}H_6P$), 4.06–3.91 (br m, 4H, OCH_2CH_3), 1.19 (t, *J* = 6.9 Hz, 6H, OCH_2CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 157.6 (d, *J* = 5.9 Hz, C_5H_4N *Q*), 148.9 (C_5H_4N), 143.8 (d, *J* = 10.1 Hz, $C_{10}H_6P$ *Q*), 135.9 (C_5H_4N), 135.3 (d, *J* = 2.5 Hz, $C_{10}H_6P$ *Q*), 132.5 (d, *J* = 15.9 Hz, $C_{10}H_6P$ *Q*), 128.3 (d, *J* = 23.8 Hz, $C_{10}H_6P$), 128.3 (C_5H_4N), 128.1 (C_5H_4N), 128.1, 127.1, 127.1, 126.4 ($C_{10}H_6P$), 124.4 (d, *J* = 186 Hz, $C_{10}H_6P$ *C*P), 122.8 ($C_{10}H_6P$), 62.0 (d, *J* = 5.6 Hz, OCH_2CH_3), 16.3 (d, *J* = 4.4 Hz, OCH_2CH_3); Mp: 97–99°C; IR (neat, cm^{-1}) = 1239, 1047, 1017, 960, 782, 747, 656, 565; Anal. Calcd for $C_{19}H_{20}NO_3P$: C, 66.85; H, 5.91; N, 4.10. Found: C, 67.23; H, 6.13; N, 4.41; HRMS (ESI^+): exact mass calcd for $C_{19}H_{21}O_3NP$ $[M+H]^+$ requires *m/z* 342.1259, found *m/z* 342.1257.

2-(2′-Methoxy-1′-naphthyl)phenyl-1-phosphine (*rac*-6). A flame-dried Schlenk flask was cooled to room temperature under vacuum, backfilled with nitrogen and charged with $LiAlH_4$ (0.041 g, 1.08 mmol) and THF (4 mL). The mixture was then cooled to -78 °C, chlorotrimethylsilane (0.14 mL, 1.08 mmol) added, resulting solution allowed to warm to RT over 30 min then re-cooled to -78 °C and 2-methoxy-1-(2′-diethoxyphosphorylphenyl)naphthylene (0.133 g, 0.359 mmol) in THF (4 mL) added. The resulting reaction mixture was allowed to warm to RT and stirred for 16 h after which degassed water (10 mL) was added and the product extracted with degassed Et_2O (2 × 15 mL). The organic fractions were then combined, washed with water, dried over $MgSO_4$, filtered and the solvent removed *in vacuo* to give the product as a white solid (0.093 g, 98 %). $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, δ): -127.8 (t, $^3J_{P\text{-}H}$ = 204 Hz); ^1H NMR (400 MHz, $CDCl_3$, δ): 7.94 (d, *J* = 9.0 Hz, 1H, $C_{10}H_6OCH_3$), 7.87–7.85 (m, 1H, C_6H_4P), 7.73 (t, *J* = 7.1 Hz, 1H, C_6H_4P), 7.44 (t, *J* = 7.5 Hz, 1H, C_6H_4P), 7.39 (d, *J* = 9.1 Hz, 1H, $C_{10}H_6OCH_3$), 7.38–7.34 (m, 3H, $C_{10}H_6OCH_3$), 7.27–7.23 (m, 2H, $C_{10}H_6OCH_3$, C_6H_4P), 3.89 (s, 3H, OCH_3), 3.59 (dd, $^3J_{P\text{-}H}$ = 204 Hz, $^1J_{H\text{-}H}$ = 12.3 Hz, 1H, P*H*), 3.54 (dd, $^3J_{P\text{-}H}$ = 204 Hz, $^1J_{H\text{-}H}$ = 12.3 Hz, 1H, P*H*); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): 153.8

($C_{10}H_6OCH_3$ *Q*), 141.1 (d, *J* = 14.0 Hz, C_6H_4P *Q*), 135.2 (d, *J* = 11.3 Hz, C_6H_4P *Q*), 133.3 ($C_{10}H_6OCH_3$ *Q*), 131.1 (d, *J* = 2.7 Hz, C_6H_4P), 130.1 (d, *J* = 212 Hz, $C_{10}H_6OCH_3$ *C*P), 129.8 ($C_{10}H_6OCH_3$), 128.4 (C_6H_4P), 128.1 ($C_{10}H_6OCH_3$), 127.5 (d, *J* = 4.0 Hz, C_6H_4P), 126.8 ($C_{10}H_6OCH_3$), 124.9 ($C_{10}H_6OCH_3$), 124.6 (d, *J* = 3.2 Hz, $C_{10}H_6OCH_3$ *Q*), 123.8 ($C_{10}H_6OCH_3$), 113.5 ($C_{10}H_6OCH_3$), 56.7 (OCH_3); IR (neat, cm^{-1}) 1258, 1069, 1010, 783; HRMS (ESI^+): exact mass calcd for $C_{17}H_{15}OP$ $[M+H]^+$ requires *m/z* 266.0861, found *m/z* 266.0863.

1-[2-(2′-Methoxy-1′-napthyl)phenyl]-2,5-dimethylphospholanium-1-yl](trihydrido)borate (7). 2-(2′-methoxy-1′-naphthyl)phenyl-1-phosphine (0.093 g, 0.349 mmol) dissolved in degassed THF (20 mL) was cooled to -78 °C and ^{n}BuLi (2.5 M in hexanes, 0.15 mL, 0.384 mmol) was added dropwise. The solution was then allowed to warm to RT and stirred at this temperature for 1 h. A solution of (2*S*,5*S*)-2,5-hexanediol cyclic sulphate (0.069 g, 0.383 mmol) in THF (10 mL) was then added at RT and stirred until the dark red solution decolourised to pale yellow (2 h). The solution was cooled to -78 °C and ^{n}BuLi (2.5 M in hexanes, 0.15 mL, 0.384 mmol) added dropwise. The solution was allowed to warm to RT and was stirred again until the dark red solution decolourised to pale yellow (20 h). The solution was cooled again to -78°C and ^{n}BuLi (2.5 M in hexanes, 0.15 mL, 0.384 mmol) added dropwise. The solution was allowed to warm to RT and then stirred at this temperature for 36 h. BH_3.THF solution (0.70 mL, 0.698 mmol) was then added at 0°C and the solution stirred at RT for 16 h. H_2O (10 mL) was then added and the solvent removed under reduced pressure. The residue was extracted with Et_2O (3 × 15 mL), the organics combined, washed with H_2O (10 mL), dried over $MgSO_4$, filtered and the solvent removed *in vacuo*. The crude product was purified by column chromatography eluting with petrol/EtOAc (5:1) to give the product as a white solid (0.033 g, 26 %). ^{11}B NMR (128.3 MHz, $CDCl_3$, *δ*): -39.6 (d, $^3J_{P\text{-}B}$ = 49.4 Hz); $^{31}P\{^1H\}$ NMR (161.8 MHz, $CDCl_3$, *δ*): 40.7 (br m); ^{1}H NMR (400 MHz, $CDCl_3$, *δ*): a 1:1 mixture of diastereoisomers 8.11–7.90 (m, 4H, $C_{10}H_6OCH_3$ + C_6H_4P), 7.84–7.81 (m, 2H, $C_{10}H_6OCH_3$), 7.58–7.50 (m, 4H, C_6H_4P), 7.34–7.30 (m, 6H, $C_{10}H_6OCH_3$), 7.23–7.18 (m, 2H, C_6H_4P), 7.15–7.08 (m, 2H, $C_{10}H_6OCH_3$), 3.84 (d, *J* = 1.8 Hz, 6H, OCH_3), 2.22–2.11 (m, 2H, PC*H*), 1.94–1.81 (m, 2H, PC*H*), 1.63–1.50 (m, 4H, CH_2), 1.31–1.12 (m, 2H, CH_2), 1.00–0.88 (m, 6H, CH_3), 0.49 (d, *J* = 6.6 Hz, 3H, CH_3), 0.47 (d, *J* = 6.7 Hz, 3H, CH_3); $^{13}C\{^1H\}$ NMR (100.5 MHz, $CDCl_3$, δ): a 1:1 mixture of diastereoisomers, 154.4 ($C_{10}H_6$ *Q*), 153.7 ($C_{10}H_6$ Q), 141.8 (d, *J* = 6.0 Hz, *Q*), 141.4 (d, *J* = 2.7 Hz, *Q*), 136.1, 135.0, 135.4, 135.3, 134.6 (*Q*), 134.4 (*Q*), 133.1 (d, *J* = 7.5 Hz), 132.8 (d, *J* = 6.8 Hz), 130.8 (d, *J* = 2.3 Hz), 130.7 (d, *J* = 2.0 Hz), 128.6 (d, *J* = 38.1 Hz, C_6H_4P *C*P), 128.6 (*Q*), 128.6 (*Q*), 128.2, 128.0 (d, *J* = 37.0 Hz, C_6H_4P *C*P), 128.0, 127.5 (d, *J* = 10.7 Hz), 127.2 (d, *J* = 9.5 Hz), 127.0, 126.6, 125.3, 125.1, 123.7, 123.6 (d, *J* = 1.7 Hz, *Q*), 123.5, 123.2 (d, *J* = 2.4 Hz, *Q*), 112.7, 112.5, 55.8 (OCH_3) 36.8 (d, *J* = 37.2 Hz, *C*HCH$_3$), 36.6 (d, *J* = 37.6 Hz, *C*HCH$_3$), 35.0 (2 × *C*H$_2$), 34.2 (d, *J* = 5.8 Hz, *C*H$_2$), 34.0 (d, *J* = 5.4 Hz, *C*H$_2$), 32.8 (d, *J* = 34.5 Hz, *C*HCH$_3$), 31.5 (d, *J* = 34.0 Hz, *C*HCH$_3$), 15.6 (d, *J* = 2.9 Hz, CH*C*H$_3$) 15.2 (d, *J* = 2.6 Hz, CH*C*H$_3$), 14.4 (d, *J* = 4.7 Hz, CH*C*H$_3$), 13.7 (d, *J* = 4.6 Hz, CH*C*H$_3$); IR (neat, cm^{-1}): 2929, 2370, 1265, 1065, 807, 730, 677; Anal. Calcd for $C_{23}H_{28}BOP$: C, 76.26; H, 7.79. Found: C, 76.58; H, 8.11; HRMS (ESI^+): exact mass calcd for $C_{23}H_{28}BOP$ $[M+Na]^+$ requires *m/z* 385.1869, found *m/z* 385.1857.

ASSOCIATED CONTENT

Supporting Information

Text giving full details of experimental procedures, characterization data for all new compounds, details of catalyst testing and, for compound **2b**, details of crystal data, structure solution and refinement, atomic coordinates, bond distances, bond angles, anisotropic displacement parameters in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org. See DOI: 10.1039/c000000x/

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Notes

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